SECTION THREE

Chapter One

The Value of Information Resulting from Instrumented Gait Analysis: The Physiatrist

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INTRODUCTION

Gait analysis has a long history and tradition, from the pioneering work of Muybridge and Inman continuing through contemporary times with the development of modern computer-based analysis systems capable of describing the kinematic, kinetic, and muscle activation patterns of gait in unusually rich detail. Over the past several decades, instrumented gait analysis has emerged as a powerful tool in the research setting. Through descriptive and experimental studies, gait analysis has advanced our understanding of normal gait, identified and quantified the biomechanical and motor control abnormalities of pathologic gait, and documented the usefulness of various therapeutic interventions. In contrast to the established role that quantitative gait analysis has achieved as a research tool, the clinical use of gait laboratories and gait analysis by physiatrists and other rehabilitation care providers is uncommon. With the exception of diagnostic and surgical planning purposes in children with spastic paralysis, which has been largely driven by orthopedic surgeons, instrumented quantitative gait analysis has not been systematically adopted for the evaluation of gait in other patient populations. In the rehabilitation literature, there are intriguing case reports of gait analysis improving patient care, and evidence that instrumented gait studies can aid in the diagnosis and determination of the pathomechanics of some gait abnormalities. However, there is not a substantive body of data that clearly identifies the groups of patients, or the gait abnormalities commonly managed by physiatrists in which instrumented studies are beneficial to overall care and function. Perhaps because of this, efforts by proponents to expand its role in the management of adults with disabling gait problems from a variety of neurological and musculoskeletal disorders has met with limited success. Moreover, and perhaps more troubling, there is little spontaneous interest or call for expanding the use of this technology by most physiatrists.

The current state of clinical gait analysis in the practice of medical rehabilitation raises several important and timely issues that the physiatrist needs to consider. These are best addressed by clearly separating the research role of gait analysis from its use as a clinical procedure. In light of the limited data and uncertainty over the role of gait analysis in the care of adults with impaired ambulation, this chapter will focus on the important conceptual and practical barriers that limit its clinical use by the physiatrist. The barriers and limitations listed in **Table 1** combine recommendations from a recent National Center for Medical Rehabilita-

Table 1.
Barriers, limitations, and unanswered questions concerning the use of clinical instrumented gait analysis by the physiatrist.

Lack of objective data that instrumented gait analysis improves patient function.

- Effect of gait analysis on diagnosis, clinical decision making, and treatment selection is unclear
- Lack of cost-effectiveness information

Limited information or guidelines for selecting and applying specific gait analysis techniques in evaluating and treating different gait abnormalities.

- Is standardization of gait analysis protocols for different disorders useful?
- Better definition of the patient populations and gait problems that are benefited by instrumented gait analysis.
- Does instrumented "motion" analysis improve the care of nonambulatory mobility problems or upper limb motor disability?

Limited treatment options for use in the management of adult gait disorders.

- Current physiatric interventions are empirically based and have low morbidity, lessening the need for instrumented gait analysis.
- Improved neuromuscular and musculoskeletal models of gait needed to allow prediction of compensatory strategies and treatment outcomes.

Limited understanding by clinicians of the data generated by instrumented gait analysis.

- Better training of residents and clinicians in the complexities of the kinematic, kinetic, and motor control features of gait
- Improved gait educational media
- Standardization of terminology to improve communication

tion Research sponsored workshop on the future of gait analysis (1) with those of other researchers (2–4) and personal observations. These barriers touch on multiple aspects of gait analysis: basic technology concerns over the ease and accuracy of data acquisition, uncertainty regarding the value of different gait measures in various disorders, and fundamental concerns over its clinical effectiveness.

An initial, useful perspective can be gained by reviewing the gait issues associated with the assessment of children with cerebral palsy (CP), the disorder in which gait analysis has achieved its greatest level of clinical acceptance. By characterizing the reasons for its relative success in *this* population, the limitations and problems that have prevented its use in the *adult* population become more clinically apparent.

The neuromuscular manifestations of CP are heterogeneous. A wide spectrum of clinical gait disorders is present in children with CP that ranges from unilateral spastic hemiplegic gait to the diplegic crouched gait pattern (5,6). Altered central nervous system motor control of gait is superimposed upon varying degrees of muscle or joint contracture and (mal)adaptive changes in skeletal growth and alignment. The result is a dynamically evolving gait pattern in a growing child caused by the complex interplay of abnormal muscle timing and force generation, secondary limitations in joint range of motion, and altered muscle force lever arms caused by skeletal adaptations of the lower limb joints. Treatment of these abnormalities involves the collaborative efforts of multiple health care providers and may include: 1) various surgical procedures done at appropriate times during the child's development, 2) the use of serial orthotic devices, 3) both invasive and noninvasive spasticity management, and 4) physical therapy. Successful optimization of a child's gait can lead to a lifetime of improved mobility, function, and quality of life, while inappropriate treatment may worsen disability.

In summary, the gait disorders experienced by children with CP are heterogeneous, complex, and involve invasive treatments, but can offer a lifetime of improved function. The use of gait analysis to characterize a child's walking pattern is intuitively rational and improves the understanding and inter-relationships between multiple complex factors unique to each child. Analysis allows the longitudinal tracking of the evolution of gait, and can assess treatment effects. There is some evidence that supports the use of surgical interventions in improving gait (7), demonstrates that gait analysis alters surgical decision-making (8), and improves clinical outcomes (9). Yet, despite the use of gait analysis in spastic paralysis for the past decade and strong advocacy supporting its use, considerable controversy still exists over its true clinical value as highlighted in the recent editorials by Gage (2) and Watts (10).

In many respects, CP gait encompasses a unique constellation of clinical characteristics that is more complex than the issues surrounding the management of gait in most adult rehabilitation settings. Hemiplegic gait following brain injury is likely the most common central nervous system gait disorder that the physiatrist must manage and serves as a useful model for understanding the role of instrumented gait analysis. Several major differences will be highlighted in this

Chapter. First, studies have shown that the altered gait motor control in hemiplegia usually falls into one of three patterns: premature activation of the plantar-flexors, reduced activity in one muscle or in muscles groups, and co-contraction (11–13). As a result, the adult hemiplegic gait pattern is more stereotypic than the diversity of abnormalities seen in children with CP. The resulting biomechanical deficits that compromise walking primarily affect knee and ankle control. Successful treatment strategies using combinations of foot, ankle, and knee orthotic devices; upper limb assistive aids; neurolytic procedures; and functional training have long been accepted as the standard of care. The principles underlying the use of orthoses and neurolytic procedures are based on generally accepted but simplified biomechanics of moment generation at the ankle and knee. While there has been some objective verification of the effectiveness of current treatments (14,15), we do not know if contemporary clinical practice maximizes gait ability. Secondly, the bony adaptations and developmental changes seen in the maturing skeleton of the child with CP are not a clinical concern in the adult. Thirdly, the surgical interventions used in these children are only rarely used in adults. Finally, expectations for what is an acceptable gait, perhaps not always to the benefit of individuals, are lower in the adult, especially the elderly person with stroke. This combination of clinical features surrounding adult hemiplegic gait has lead to a general acceptance of a relatively nonaggressive, noninvasive treatment paradigm that has not changed substantially for many years and typically does not attempt to understand the gait disorder with the degree of detail that can be obtained with instrumented gait studies.

Issues That Must be Addressed Before Clinical Gait Analysis Will be Used by Physiatrists in the Treatment of Adult Gait Disorders

Lack of Objective Data that Instrumented Gait Analysis Improves Diagnosis and Treatment Outcomes Over Standard Visual Observation Techniques

The lack of convincing data that instrumented gait analysis is more effective in improving diagnosis or treatment outcomes than standard clinical visual observation techniques is one of the most important issues that needs to be addressed. Visual observation of gait is the clinical standard and trained observers typically believe they can recognize many gait deviations, correctly assess the cause of the deviation, and infer an appropriate treatment strategy (16). This is probably true in gait problems resulting from musculoskeletal or peripheral neurologic disorders isolated to a single joint or nerve, but the reliability of visual observation in the more complex gait disorder associated with central motor control abnormalities is probably poor. The limited number of studies on observational gait analysis supports this concern by consistently showing that the interobserver reliability of visually identified kinematic deviations is only fair to moderate (17–19). If reliability is only fair in simply identifying motion abnormalities, it is undoubtedly even less reliable in accurately predicting the timing or pattern of alterations in muscle activation and/or the joint kinetics that underlie the movement disturbances (20). The limited reliability of visual observation would argue, empirically and intuitively, for an expanded role of instrumented gait analysis. Before this can be accepted, two issues need to be resolved: 1) whether instrumented gait analysis is more reliable and reproducible than visual gait analysis and 2) whether the increased time, effort, and expense of instrumented gait analysis affect treatment decision-making and functional outcome.

The reliability and reproducibility of instrumented gait analysis has received only limited study. Basic intertest reproducibility of kinetic and kinematic measurements appears to be adequate for clinical purposes (21,22). Empirically and intuitively, it is believed that quantitative gait information would improve interexaminer reliability in the identification of gait abnormalities, but this has not been adequately studied. The reliability of expert interpretation of gait studies and subsequent treatment recommendations is unknown but has been questioned (10).

Little published data directly address the effect of gait analysis on changing treatment or altering functional outcomes. While limited data exist showing that gait analysis improves the management of children with CP (8,9), clinicians must use case reports and indirect evidence to determine the value of gait analysis in other gait disorders. Case reports have highlighted the value of gait analysis in selected individuals (23–25) but do not constitute sufficient evidence to justify its widespread, general use. Examples of indirect evidence supporting the clinical use of gait analysis come from studies that suggest quantitative gait examination can identify abnormal and possibly injurious joint force development (26), predict response to botulinum toxin use in spasticity control during walking (11), and aid in the choice of the most appropriate therapeutic technique or orthotic intervention in stroke (20). The lack of a substantive body of evidence of its clinical value is surprising and somewhat worrisome given that it has been available as a clinical procedure for nearly a decade. This is especially problematic given the current financial pressures on health care systems to justify the use of any new or expensive intervention.

Limited Information and Guidelines for Selecting and Applying Specific Gait Analysis Techniques in the Evaluation and Treatment of Different Gait Abnormalities

Gait analysis encompasses a wide range of measurement technologies designed to capture and characterize the temporal, spatial, kinematic, kinetic, and muscle activation pattern of an individual's gait. Kinematic procedures measure the motion of the body and limb segments through space during representative walking strides. Markers are placed over predefined bony landmarks on the arms, trunk, pelvis, and legs. The markers are used with a variety of image-capture technologies to track the three-dimensional locations of individual body segments throughout a gait cycle. From this raw coordinate data, joint range of motion and angular velocities are calculated for clinical analysis.

Kinetic analysis is used to determine the net forces and torques (moment) exerted on the body as a result of the combined effects of the ground reaction force, inertia, and muscle contraction. Kinetic analysis requires the simultaneous (i.e., during the same gait cycle) collection of kinematic information and ground reaction forces. Ground reaction forces are collected as subjects walk over force plates embedded into the floor of the laboratory. The calculation of the forces and moments generated at each joint is based on inverse dynamics physics and simplified models of the musculoskeletal system.

Dynamic electromyography (EMG) is used to determine the timing of muscle activation and to crudely estimate the relative magnitude of muscle contraction. EMG data can be collected using surface electrodes or, when greater muscle specificity is needed, intramuscular wire electrodes. The EMG signal is amplified and transmitted via telemetry or cable to a central computer where it is synchronized with kinematic and kinetic data, thus allowing inference about the muscular sources of force and motion abnormalities.

Separating the cause(s) of an abnormal gait from adaptive and potentially beneficial compensatory strategies used by an individual is not necessarily straightforward. The multiplicity of the central and peripheral mechanisms associated with the control of gait leads to a degree of indeterminacy in understanding any particular gait pattern. This is made worse by the absence of good models of the neuromuscular control strategies adopted by persons with different disorders that affect walking. Thus, there is a tendency to collect the entire spectrum of gait information in order to maximize the likelihood of measuring the relevant and important discriminating kinematic, kinetic, and muscle-timing features of a particular gait pattern. From a practical standpoint, this adds to the cost, complexity, and time required for gait analysis, especially in pathologic gait situations where increased stride-to-stride variability, balance deficits, and/or cognitive limitations interfere with data collection. The relative importance of the various subcomponents of gait analysis—kinematic, kinetic, and EMG, either individually or in combinations to the diagnosis or treatment of different gait abnormalities—is unknown.

The situation is analogous to the electrodiagnostic evaluation that is performed to "rule out neuromuscular disease." In the absence of a more specific clinical question, testing tends to be extensive, poorly focused, time consuming, and often of unclear clinical utility. Instrumented gait analysis may achieve greater clinical acceptance and be more cost effective if analyses can be focused on answering specific clinical questions. As a hypothetical example, consider the person with genu recurvatum following a traumatic brain injury. Recurvatum may result from several motor control abnormalities (premature plantarflexor muscle activity, prolonged quadriceps activation) or as overcompensation for absent quadriceps activity. To distinguish between clinically relevant causes, a directed gait study might only require dynamic EMG recording from the quadriceps and plantarflexor muscles along with footswitch information to determine the timing of muscle activation relative to heelstrike and toeoff. Such a gait study would obviously not completely characterize the individual's gait or allow comment on other potentially treatable abnormalities, but would be simple, require little time, and would likely be more cost effective.

Limited Treatment Options for Use in the Management of Adult Gait Disorders

The interventions commonly recommended by physiatrists for treating gait disorders can be broadly classified into one of several approaches: 1) physical therapy based task training to improve functional skills; 2) orthotic, prosthetic, and assistive devices to improve balance, alter biomechanical forces, or control joint positioning; and 3) spasticity management with systemic drugs or local neurolytic procedures.

Physical therapy is seldom if ever detrimental but the selection of specific modalities or techniques is empirical and not well-based on objective information. It is not known whether gait analysis can help in choosing the best treatment approach, predict response to treatment, or determine if maximal recovery has occurred. Lower limb orthotic devices have seen substantial evolutionary advances in materials and options over the past several decades but there has been little fundamental improvement in their effect on the abnormal biomechanical or neurophysiologic features of gait. Prescription is based on well-accepted biomechanical principles, which can be modified as needed and, when clinical uncertainty exists, can incorporate adjustable joints to allow empirical gait optimization. How will gait analysis improve the prescription of lower limb orthoses: better device selection, defining optimal joint position, identifying persons for whom orthoses are inappropriate? These are questions for which answers do not yet exist. Neurolytic procedures, while variably successful and difficult to titrate, can be safely performed, especially if limited to motor point or motor nerve blocks. The effects of blocks are generally limited to months, lessening the risk of any permanent unexpected adverse effects on gait. When uncertainty exists, is it easier and more efficient for patients and clinicians to perform temporary local anesthetic blocks that may give both diagnostic and therapeutic information than to perform an instrumented gait analysis? How much of the advantage of "instrumented gait analysis" comes from quantitative measurements as compared with simply the clinical evaluation by an experienced consultant/expert in gait?

For the adult with a major disability, gait dysfunction is usually only one aspect of the overall impaired functioning. The emphasis and effort placed on improving gait is more or less important depending on other coexisting cognitive, sensorimotor, and pyschosocial problems. When the clinical features of currently available rehabilitation interventions (low acute morbidity, limited risk of long-term adverse sequalae, empirical application, and variable impact on overall function) are combined with uncertainty about the effectiveness of gait analysis in improving treatment and outcome, the current standard of care based on simple clinical assessment and judgment appears clinically rational and appropriate. The risk to continuing this seemingly appropriate observational approach is the lost ability and opportunity to critique and measure our treatment effectiveness, to uncover their limitations, and to encourage us to develop better therapeutic strategies.

Justifying the use of instrumented gait analysis in the vast majority of patients will be difficult until there are better treatment options that either require greater selectivity in their application, place individuals at greater risk of injury or adverse effect, or are costly. Surgical procedures for tendon lengthening, release, or transfer have been recommended for selected adults but their use is sporadic and not generally available. A more systematic assessment of their utility in adults seems warranted. Recently, two new treatment modalities have become clinically available that may fit these criteria: botulinum toxin for treating local muscle spasticity and intrathecal baclofen pumps for use in persons with brain disorders. While the role for these treatments are currently being investigated, both potentially may be important advances in our ability to improve gait and mobility problems associated with increased muscle tone. These treatments are expensive and, in the case of baclofen pumps, invasive. The value of instrumented gait analysis in these settings is largely untested but may be useful in predicting therapeutic response (11) or as a tool for objectively documenting effectiveness, thus justifying the use or continued use of these interventions.

Limited Understanding by Clinicians of the Kinematic, Kinetic, and Electromyographic Data Generated by Instrumented Gait Analysis

Instrumented gait analysis can generate an overwhelming amount of data describing the complex temporal, spatial, and kinetic aspects of an individual gait pattern. Interpreting this information requires a detailed understanding of gait biomechanics, normal and abnormal patterns of motor control, and an ability to relate these features to the pathological motion that is observed during walking. Finally, integrating this understanding of the mechanisms underlying a gait abnormality into appropriate and useful clinical recommendations requires substantial experience. Gait analysis reports, even after being subjected to an interpretive summary by an expert, tend to be long and difficult to understand for the clinician without specific training or interest in gait. This is not particularly unusual or unexpected for a highly specialized medical test, but does serve to further distance non-specialist clinicians from instrumented gait analysis and places them in the position of needing to act on information that they may not fully understand.

For physiatrists, this is unfortunate, since many of the patient populations that constitute the core of rehabilitation medicine have significant gait disability. Assuring expertise in the evaluation, diagnosis, treatment, and management of gait disorders is an important and integral part of maintaining control over this aspect of care. Achieving this level of expertise will require that contemporary concepts of gait be incorporated into training programs and continuing medical education programs, facilitated through clinical interactions with patients, and updated as new advances in gait therapeutics are developed. Contemporary general rehabilitation texts (27,28) that serve as a foundation for training and clinical care all include chapters on gait analysis, but do not adequately develop the necessary knowledge base that physiatrists need to adequately evaluate and understand the relationships between observational, kinematic, kinetic, and EMG aspects of gait. Instrumented gait analysis offers a unique and powerful tool for teaching these concepts and, in this context, is a vastly underutilized educational resource. Experts in gait need to develop more effective teaching methods and media for clinician education with one possible approach being the use of computer multimedia as demonstrated by Smith (29).

Raising the general level of awareness of gait biomechanics can improve clinical observational gait analysis skills and, at the same time, increase the awareness of the uncertainties inherent in current clinical approaches to gait evaluation and the need for more objective testing in selected individuals. An alternate approach to expanding the number of clinicians skilled in gait analysis is through the automation of analysis using artificial intelligence based gait diagnostic systems (30). This approach, while intriguing, will need to overcome the biases and difficulties other expert systems have had in achieving clinical acceptance and widespread use.

CONCLUSION

The research role of gait analysis in improving our understanding of the basic neurobiology and mechanics of gait and in assessing the value of new interventions seems assured. However, the role of instrumented gait analysis in the management of those individuals served by physiatrists faces an uncertain future. As the health care system finds itself under increasing pressure to financially justify the use of expensive diagnostic tools and treatment interventions, the lack of convincing data that expanding the use of gait analysis will improve patient function makes it difficult to argue forcefully for its use at this time. The path to increasing the role of clinical gait analysis lies in proving its value through additional case studies but more importantly through controlled studies demonstrating its effectiveness. Further development in gait laboratory technology to improve access, automation, ease of use, and cost is needed. Improving the education of clinicians in the quantitative pathomechanics of abnormal gait will not only improve traditional clinical care but will force clinicians into recognizing the ambiguities and limitations of visual observation, especially when costly or invasive treatments are involved.

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